NbN Josephson and Tunnel Junctions for Space THz Observation and Signal Processing

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ABSTRACT: *Active superconducting circuits based on picoseconds switching, i.e. THz oscillating, Josephson tunnel junctions are expected to find a large domain of applications in spatial sub-millimeter wave and FIR detectors as well as in satellite based wideband signal and data processors. In the first case SIS (superconductor-insulator-superconductor) tunnel junctions are required, while in the second case SNS (superconductor-normal metal-superconductor) self-shunted junctions are preferred. We present the advantages of the nitride junction technology currently developed at CEA-Grenoble, based on high-performance MTS (medium temperature superconductor) NbN films in both SIS and SNS junctions. In the SIS case the device performances rely on a sputter deposited and post-annealed, only 0.5-0.7 nm thick, dielectric MgO barrier. This leads to junctions with a Josephson critical current in the range of 10-25 kA/cm², and a large superconducting energy gap (> 5 meV) associated with a low sub-gap quasi-particle leakage current. These parameters are suitable for low "noise temperature" heterodyne mixers, local oscillators, and integrated receivers in the 0.8 to 1.4 THz frequency range. In the SNS case, a new reactively sputtered Ta_XN barrier material has been developed. The obtained junctions have a characteristic Josephson frequency above 350 GHz. This can be easily extended above 800 GHz by barrier parameter engineering, and reducing the junction size by using conventional submicron lithographic techniques. Such NbN SNS junctions have been shown to be suitable for large scale integration in nitride-based multilayer Rapid Single Flux Quantum logic circuits operating at 10K. Both NbN SIS and SNS junction circuits can be combined on-chip in new ultra-wide band and low dissipation front-end SOC functions operating near 10K. In addition, they can be eventually interfaced with higher temperature semiconductor stages for space telecom applications.*

1 - INTRODUCTION

Among the various alternative technologies to silicon-based electronics, superconductive Josephson junction devices surely deserve a close examination. Despite the major constraint of using cryogenic temperature stages (2 to 77 K), superconducting junctions allow operating frequencies easily above 100GHz with power dissipations of about one hundred or less of the actual CMOS standards [1]. Given that silicon transistors development projections clearly foresee short-term technology saturation, end-users raise their interest

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toward superconductive electronics [2]. Analysis and telecom spatial applications constitute indeed one of the primary application fields for this new potentially breaking-through technology [3].

Great efforts are spent looking for the materials which give the best junction and integrated circuit performances. The generation of Josephson junctions based on niobium as electrode material is still matter of interest worldwide thanks to its high degree of reliability, associated to the use since 1983 of alumina tunnel barriers, and thanks to a trilayer-based processing technology [4].

Since 1987 international resources have been largely spent to obtain reliable junctions by using high critical temperature superconductor (HTS) based on either cuprate (YBaCuO,..) or borides (MgB_2,..) films. However, beside some interesting realizations of specialized active circuits including a very limited number of junctions, there is practically no expectation of engineering thousands of junctions with low characteristic parameter spread in high Tc materials. This is due to the over rich and complex families of chemically either stable or unstable defects contained in metallurgical cuprate and boride phases of the films. Another reason lies in the anisotropic and complex electronic and superconducting properties of such low crystalline symmetry materials, which require delicate hetero-epitaxial multilayer growth and selective etching techniques.

Nb junction performances are constrained at high frequencies. For SIS tunnel junctions applied to heterodyne receivers the relatively low energy gap of Nb introduces a cutoff frequency at about 650 GHz. Logic Nb circuits, which require damped junctions, are limited to top switching frequencies of about 250 GHz. In order to damp a Nb junction, the alumina barrier capacitance has to be externally shunted by a resistor or substituted by a suitable self-shunted metal barrier. However metal barrier Nb junctions with a suitable high frequency cutoff have not yet been realized. Finally, Nb circuits can not operate at temperature higher than 4K. This last constraint increases the cost, the weight, and the power consumption of the required cooling system, thus representing a handicap for space applications.

Niobium nitride (NbN) is a reliable conventional BCS material, and a medium temperature superconductor (MTS) in its cubic phase. We believe that this material constitutes a more appropriate choice than Nb both for analog SIS and for digital technologies. NbN junctions with a large energy gap (gap frequency about 1.45 THz) allow pushing the circuits operations up to 800 GHz at temperatures up to 12 K, twice higher than Nb [4,5].

2 – FILM DEPOSITION

2.1 – NbN FILMS

NbN layers are deposited via DC-magnetron sputtering in an argon-nitrogen controlled atmosphere. The film quality is strongly influenced by the choice of the substrate and the chamber temperature during deposition. Several substrates have been employed: sapphire, MgO, silicon and SOI.

When NbN sufficiently thick films are deposited on a substrate heated above 350°C, X-ray diffraction studies highlighted the concurrence of two different crystalline film textures: a hexagonal and a cubic phase, the last one being addressed as essential to the superconductive transition [6]. This fact has been confirmed by the R-T characterization of the films, where NbN samples with a prevalent hexagonal phase show a metal-superconductor transition which is below the usual values (T_c<7K), and is not well defined.

Films grown at high temperature (~600°C) show a better epitaxy compared with those realized at ambient temperature [6]. Moreover a thin MgO (100) buffer placed right before the NbN layer has been found to favor a correct epitaxial growth of the film [7]. SOI and Si/SiO_2 substrates need such MgO buffer to be suitable for superconducting applications [8].

2.2 – BARRIER FILMS

MgO has been chosen as trilayer barrier for several reasons. Firstly it is a good dielectric material, and well covers under-layer surfaces with self texturing properties at low deposition temperature (< 350° C). On second place, its lattice constant is close to the one of NbN, which enhances NbN counter-electrode grain growth and favors texturing.

Ultra thin MgO barrier layers (~0.6 nm thick) have been RF-magnetron sputtered with a good uniformity by applying substrate rotation. MgO has been grown in-situ in the same chamber where NbN electrodes are deposited in a sequential controlled process. As shown later in the text, the MgO dielectric barrier tunnel transparency can be decreased in a controllable way, and improved in terms of quality factor by a defined thermal annealing at about 250°C [6,7,8,9].

Ta_XN is an interesting nitride barrier for different reasons. First of all, its crystalline lattice and chemical properties are close to the one of NbN, so that the barrier can easily grow over the electrode and vice-versa. Moreover, the Ta_XN electrical barrier properties can be tuned by using two control parameters: the nitrogen-versus-argon gas flow rate during deposition and the film thickness [10,11,12,13].

Several Ta_XN films have been DC-magnetron sputtered over silicon substrates and then characterized. Table 1 resumes the samples proprieties, including the estimated thickness. Figure 1 shows the resistance of the various films as a function of the temperature. From sample A2045 to sample A2049 the Nitrogen rate has been successively reduced in order to obtain films with smaller resistance. The superconductor transition of the sample A2049 (T_c~4K) has been a positive result. Since we are looking for metallic films with higher resistance, in the sample A2051 we have further reduced the deposit thickness, increasing so its resistance by a factor 10000. Meanwhile the sample is still superconductive, with a T_c lower than 1K.

Sample Number	*Deposition Time (s)*	*Nitrogen Flow (sscm)*	*Thickness (nm)*	*Resistivity (Ω/cm)*
A2045	30	51.9	30	3.1E8
A2046	40	53.3	40	4.55E8
A2049	60	30.9	50	1.16E4
A2051	9 s	37.1	17	4E8

Table 1: List of TaN samples with relative thickness. Samples are realized over Si substrate, except for A2045, grown over a Si/SiO2 substrate.

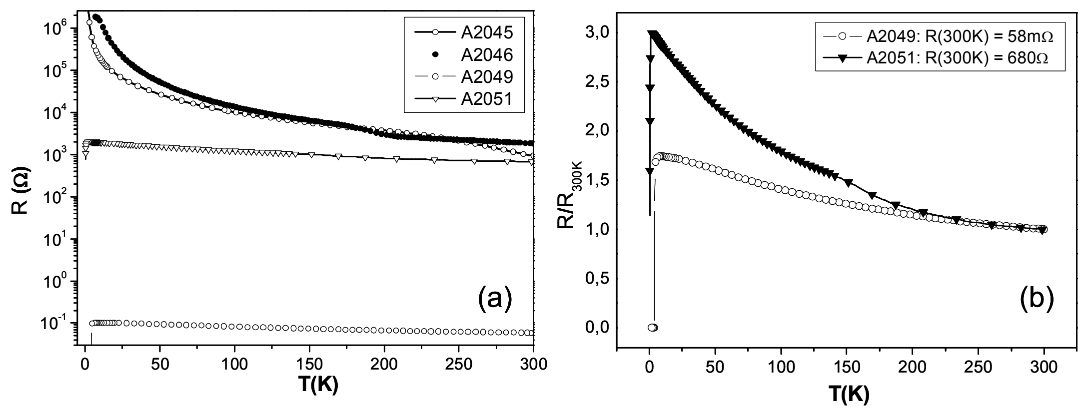

Figure 1: Resistance as a function of the temperature for the TaN samples. Films with a higher nitrogen flow rate (figure a) show an insulating behavior, while films in figure b with a lower nitrogen contribute present a clear metal-superconductor transition.

By choosing one of the two barrier materials, either MgO or Ta_XN, and by opportunely tuning their parameters, it is possible to cover a wide range of barrier resistances, which show either a metallic or an insulating behavior. NbN-MgO-NbN SIS and NbN-Ta_XN-NbN SNS junctions can be thus adapted to a large domain of applications, with only slight modifications of the junction and circuit processing. To conclude, table 2 summarizes the deposition parameters for the different materials, including the insulators, SiO_2 and Si_3N_4, and the gold used for the plots metallization [9].

Layer	*Sputtering Mode*	*P_{Ar}/P_{total} (10^{-2}mbar)*	*Power (W/cm²)*	*Deposition rate (nm/mn)*
MgO_{Buf}	RF-MAG	1.25/1.35	3.1	10 (Static)
MgO_{Bar}	RF-MAG	1.25/1.25	2.55	0.9 (Rot.)
Ta_xN	DC-MAG	1.65/1.90	2.1	60 (Static)
NbN	DC-MAG	1.70/1.89	11	320 (Static)
NbN_x	DC-MAG	1.60/1.63	4	30 (Rot.)
SiO_2	RF-MAG	0.30/0.30	4.0	13 (Rot.)
Si_3N_4	RF(BIAS)	1.00/1.00	1.3	7.5 (Static)
Au	RF	3.00/3.00	1.7	6.0 (Rot.)

Table 2: Film Deposition Parameters

3 - SIS JUNCTIONS

In a SIS junction the two superconductive electrodes are separated by a thin insulating layer (1 nm thick or less). The charges and Cooper pairs transport is therefore ruled by tunneling phenomena [7]. Figure 2 and 3 show the I-V characteristic of a NbN/MgO/NbN junction with a 0.6 nm thick tunnel barrier. The junction is strongly hysteretic and has a current density of 15 kA/cm².

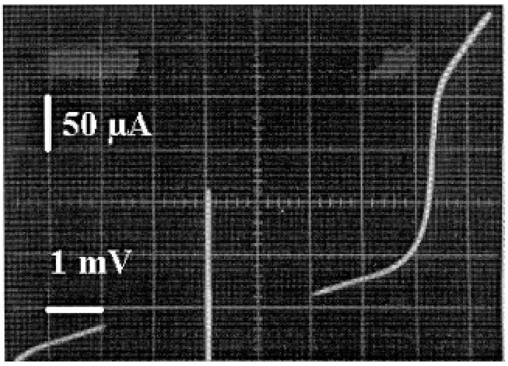

Figure 2: **1.1 µm diameter NbN/MgO/NbN tunnel junction I-V characteristic at 4.2K. The sample shows a critical current of 15kA/cm² and a clear hysteresis.**

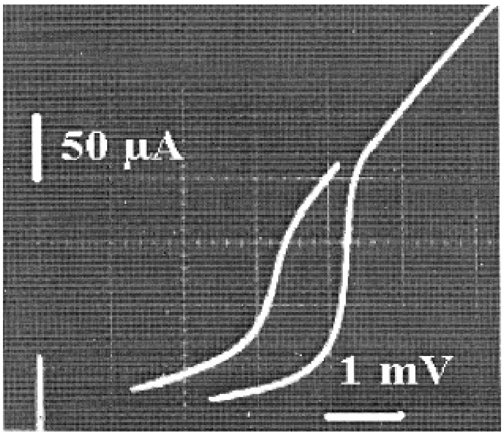

Figure 3: **I-V curve of the same junction as in figure 2 measured at 12 K with its DC-Josephson component (J_c = 10 kA/cm²); the (lower) quasi-particle curve at 4.2 K is also shown.**

A trilayer post-baking has been found effective to improve the junction electrical properties. After annealing, we have found an improved product R_nI_c and a smaller recapture current, with a reduction of the critical current which is still acceptable. Samples are usually heated at 250°C for about 1 hour [14]. Figure 4 shows the decrease of the critical current density as a function of the annealing time, plotted for different heating temperatures [8].

The MgO barrier annealing process has been clearly interpreted in the frame of a diffusion process which make MgO more dense, leading to an increase of the tunnel barrier potential height [7,14]. The benefit of such MgO barrier annealing has been clearly demonstrated in SIS heterodyne receivers, making possible to obtain better circuits with improved performances [14].

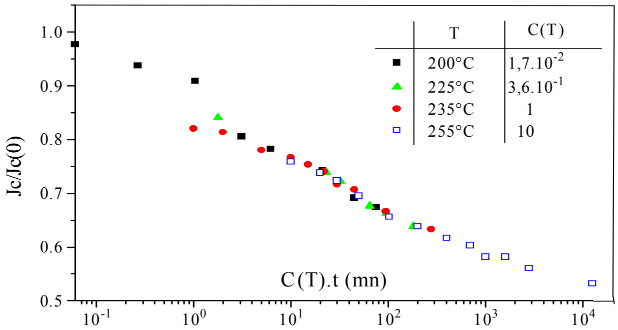

Figure 4: Controlled normalized decrease of J_c versus MgO barrier annealing time for annealing temperatures between 200° C and 255° C. C(T) is a time scaling pre-factor experimentally determined for each temperature.

Figure 5 is an example of NbN-MgO-NbN SIS THz heterodyne mixer application. The mixer has been developed on 2 µm thick Si_3N_4 membranes prepared on partially etched silicon substrate in order to insert the RF antenna inside a waveguide [8].

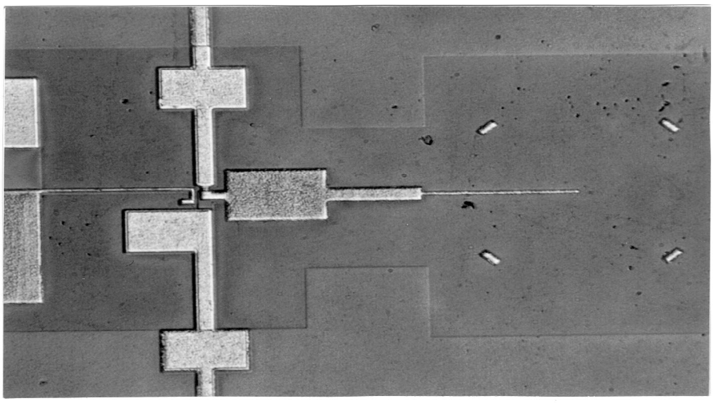

Figure 5: Detail of the junction and stub antenna (80 µm long) crossing the wave guide in a 1.5 THz membrane NbN-MgO-NbN SIS mixer (the picture covers a 1.5x1.5 mm² area) in front of a waveguide. DC Josephson current is suppressed in the 1 µm² area SIS junction via an integrated control line (left in the figure).

4 - SNS JUNCTIONS

SNS junctions present a naturally self-shunted I-V characteristic, and are therefore particularly suitable for RSFQ logic applications. Derived from the Josephson equations, the Mc Cumber parameter βc is defined as [15]:

$$\beta_c = \frac{2\pi I_c R_n^{\,2} C}{\Phi_0}, \qquad (1)$$

where I_c is the junction critical current, R_n and C are respectively the resistance and the capacitance values of the junction equivalent model, and Φ_0 is a constant. The Mc Cumber parameter describes the hysteretic behavior of the junction. SIS junctions have a βc larger than one, while RSFQ logics require values slightly smaller than 1 [16]. Junctions with a βc too small have also to be discarded, because their R_nI_c product tends to be too low, limiting the Josephson frequency [16]:

$$f_{\max} = \frac{2e}{h} R_n I_c \approx 483.6 GHz / mV \cdot R_n I_c \qquad (2)$$

Figure 6 shows the characteristic of a NbN/Ta_xN/NbN junction with a surface of 10 µm² achieved at a deposition temperature of about 450° C. The sample is nearly non-hysteretic, with a current density of 4 kA/cm² and a R_nI_c product around 0.7 mV at 4.2 K, which gives a maximum characteristic frequency of 340 GHz. To realize the presented sample, a 5 masks fabrication process has been developed at CEA-Grenoble, in which the base electrode constitutes also the ground-plane of the circuit [13].

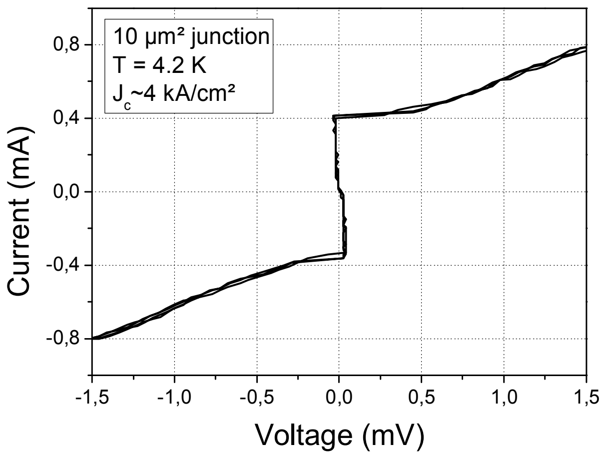

Figure 6: 10µm² NbN/TaN/NbN Josephson junction with a critical current density of 4 kA/cm² and a R_nI_c product of 0.7 mV, that corresponds to a characteristic Josephson frequency of ~340 GHz.

Figure 7 and 8 show the temperature dependence of respectively the critical current density and the R_nI_c product [13]. The curves follow the long ($d > \xi_N$) diffusive SNS Josephson model [17]:

$$J_C(T) \propto \Delta^2(T) T^{1/2} \exp\left[-\frac{d}{\xi_N(T_C)} \left(\frac{T}{T_C} \right)^{1/2} \right], \qquad (3)$$

where d is the thickness and ξ_N is the coherence length of the barrier.

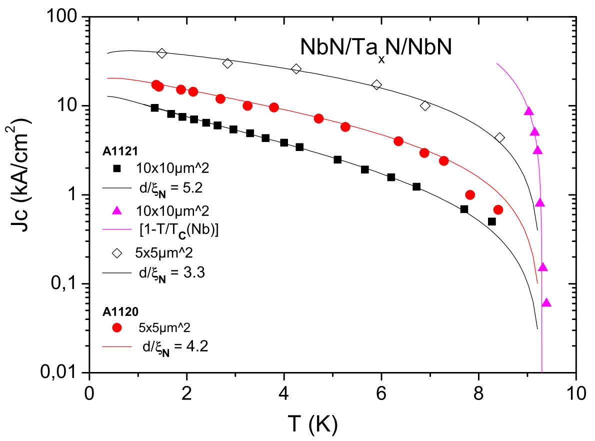

Figure 7: Temperature variation of the Josephson critical current of junctions selected on two wafers. The fitting parameter is d/ξ_N (T_c).

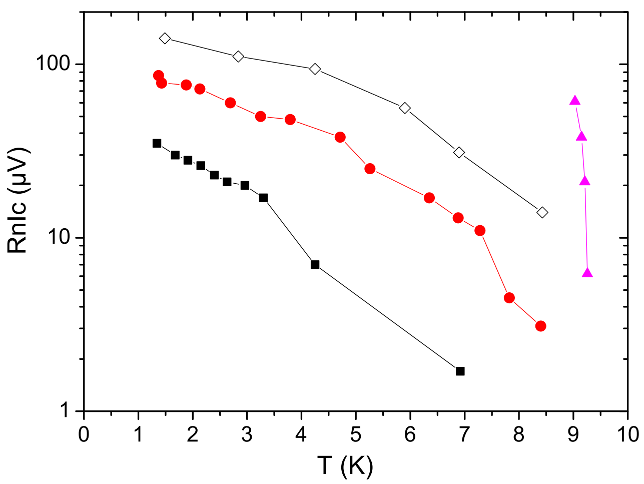

Figure 8: R_nI_c product versus temperature for the same junctions of Figure 4.

A new 7 masks process is presently developed at CEA-G in order to integrate both RSFQ gates and arrays of 1000 NbN/Ta$_x$N/NbN junctions. This process will add an independent ground-plane, allowing more complex circuit architectures and integration to micro-strip components such as antennas and resonators. As advantage, this new process will be fully compatible with the one already developed, in a way that it will be possible to either keep or remove the common ground-plane by excluding the relative masks.

5 - CONCLUSION

NbN has been studied as junction electrode because of its high critical temperature (~16 K) and its large energy gap (~1.4 THz), which leads to operating frequencies up to 450 GHz. NbN films have been deposited over several substrates at different temperatures (from T_{amb} to T~ 600° C), showing that heating during deposition and post-annealing at an intermediate temperature (300° C to 450° C) improve the junction electrical properties. MgO buffer layers have been added to ease the textured growth of the NbN films, and to improve its superconducting properties especially on SOI and Si substrates. Ta$_X$N damped barrier films have also been studied for RSFQ circuits. High-resistance semi-metallic films have been obtained with good characteristics by changing the film thickness and the nitrogen gas flow ratio in the sputtering chamber.

Superconductive Josephson junctions, both SIS (MgO tunnel barrier) and SNS (TaN semi-metallic barrier) have been studied. In the first case, a 0.6 nm thick barrier allowed to obtain a 15 kA/cm² current density. SNS junctions have been fabricated with a critical current of about 4 kA/cm² and a R_nI_c product of 0.7 mV which means an upper gate frequency of 340 GHz.

The characteristic frequency can be easily extended above 800 GHz by barrier parameter engineering, and reducing the junction size by using conventional submicron lithographic techniques. Finally such NbN SNS junctions have been shown to be suitable for large scale integration in nitride-based multilayer RSFQ logic circuits operating at 10K. Both NbN SIS and SNS junction circuits can be combined on-chip in new ultra-wide band and low dissipation front-end SOC functions operating near 10 K. In addition, they can be eventually interfaced with higher temperature semiconductor stages for space telecom applications.

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